The Effects of Shot Peening Highly Loaded Compression Springs

SAE Fatigue Design & Evaluation

Eden Prairie, MN (May 2018)

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Speaker Information

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Participating Companies

Winamac Coil Spring (Kewanna, IN)

Proto Manufacturing (Taylor, MI)

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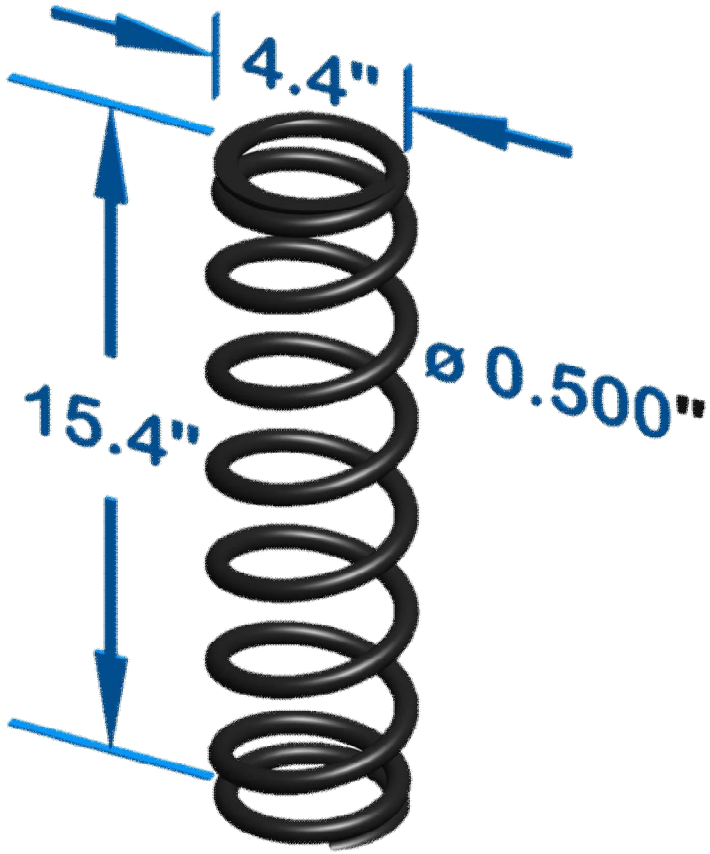
Introduction

- Evaluate the effects of fatigue life using various shot peening techniques on a severe duty spring
- Correlate the fatigue results with residual stress measured via XRD

Spring & Fatigue Test Description

- ASTM A 401 Cr-Si Wire
  - Min TS: 280 ksi

- Fatigue Test Range:
  - 13.7” to 5.25” stroke
    - ~ 2” to 10” deflection
    - 61.5% of Min TS @ max deflection



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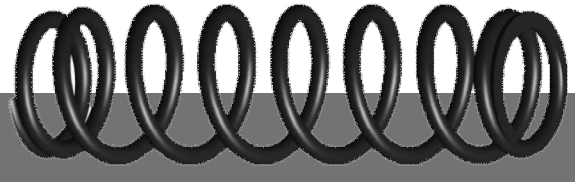
Fatigue Test Setup



Shot Peening

- Impacts From Small Media Leave Surface in Residual Compression
- Residual Compressive Stress Lowers Applied Tensile Stress
- Must Be Carefully Controlled for Repeatable Performance

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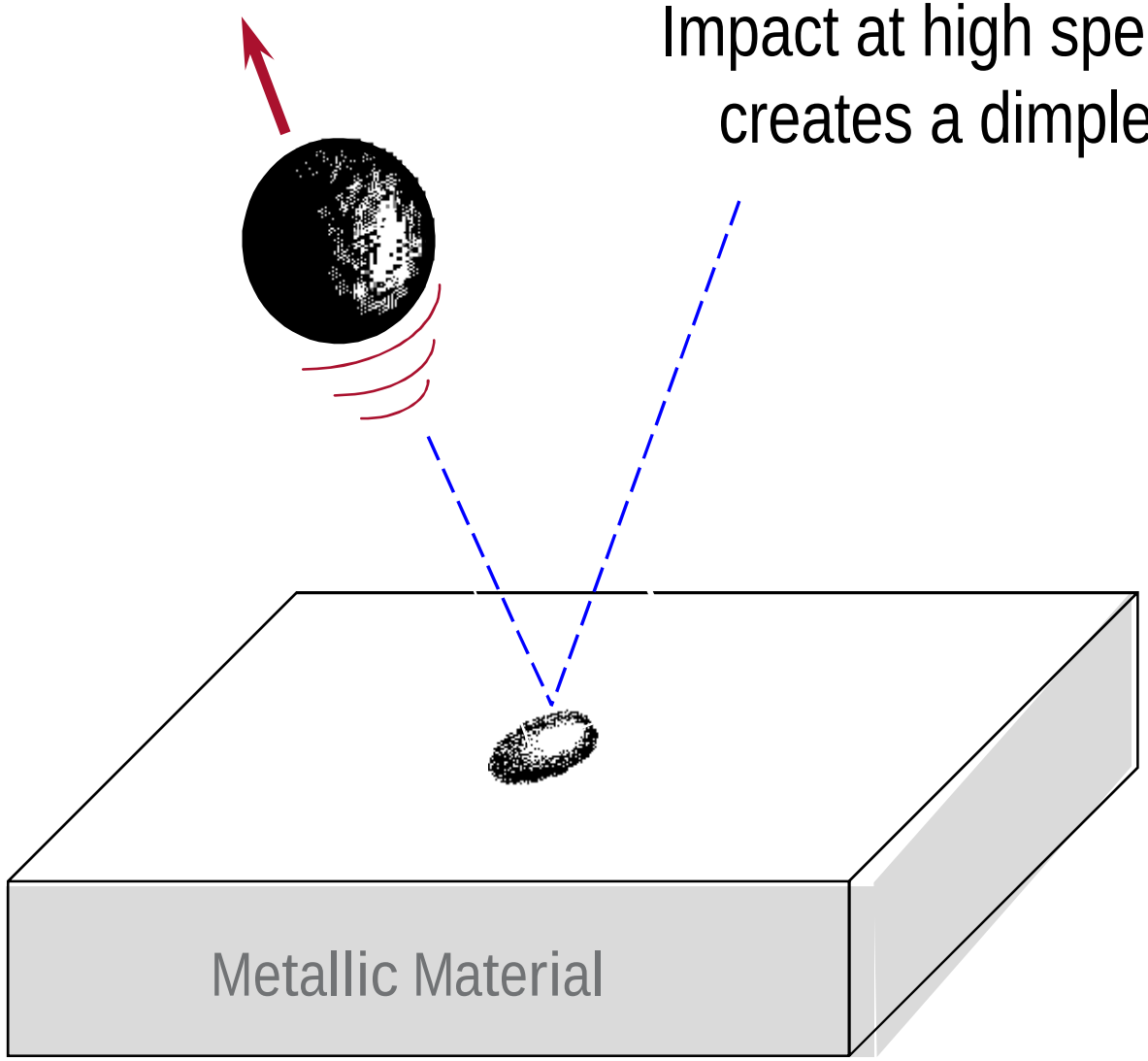
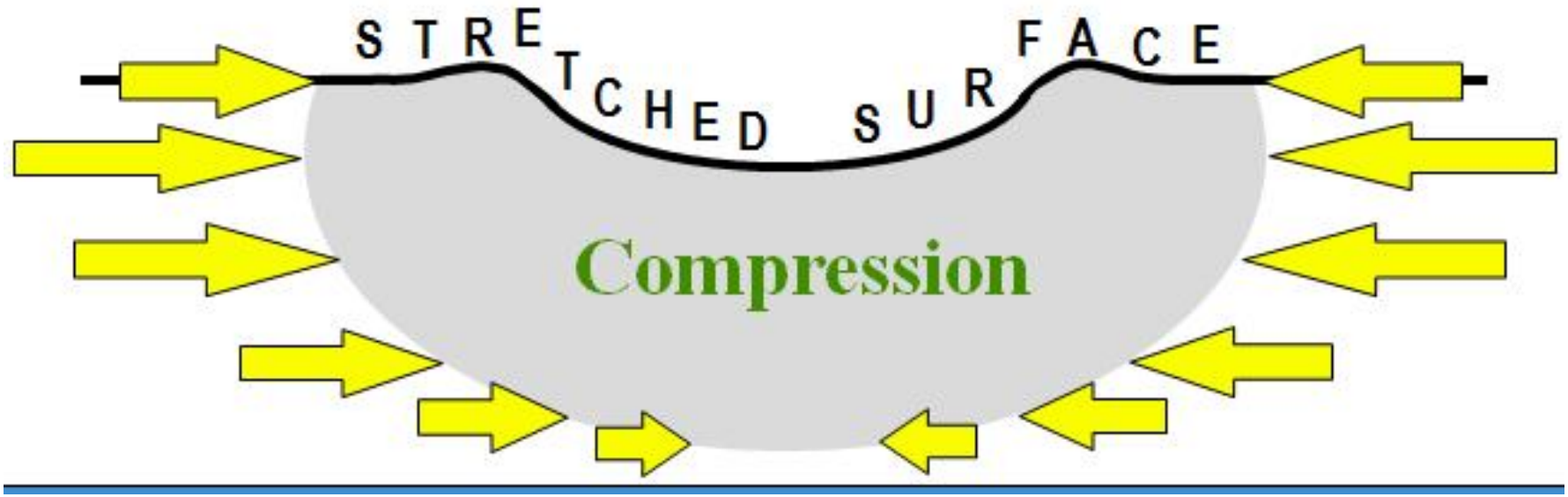
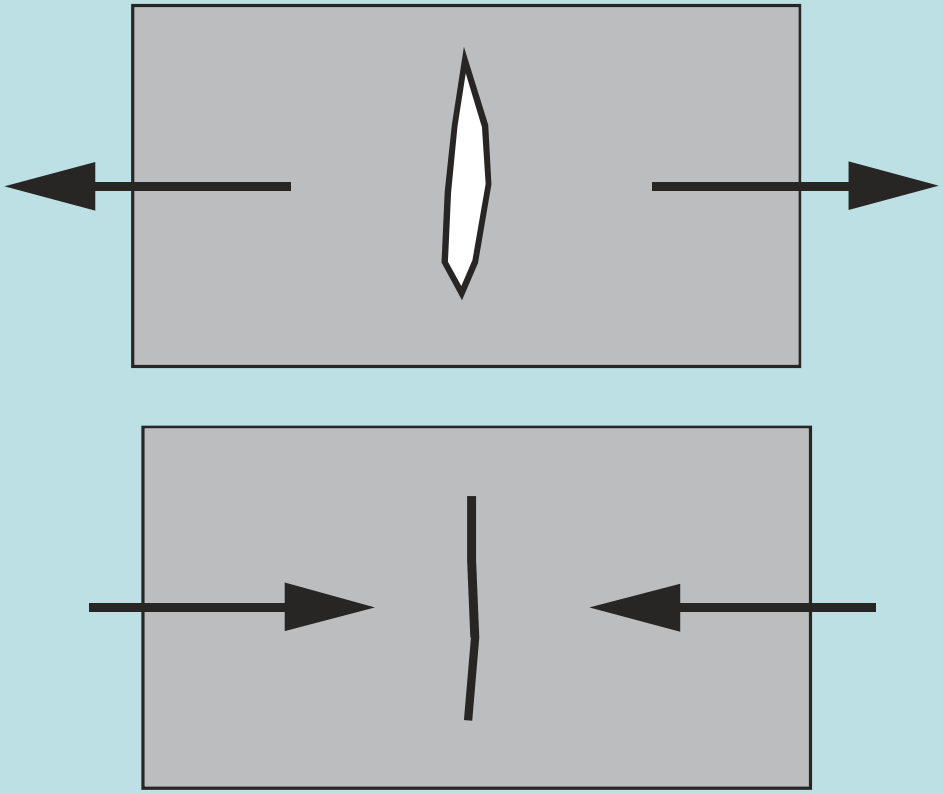
Impact at high speed creates a dimple



Development of shot peening compressive stress



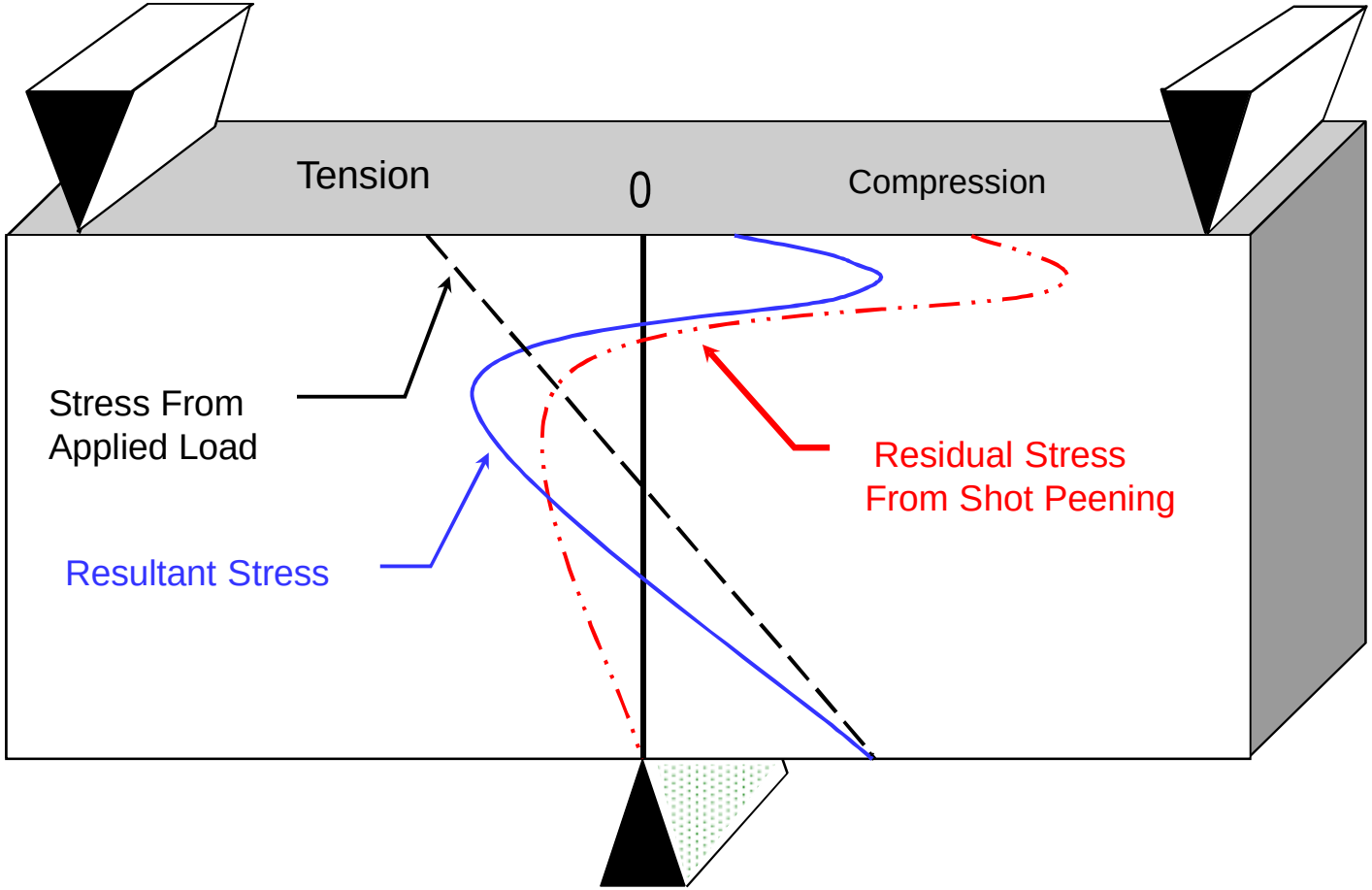
Residual Stress - Effect on Cracks



Tensile residual stress
opens crack and increases crack propagation

Compressive residual stress
closes crack and slows crack propagation

Total Stress = Applied + Residual Stress



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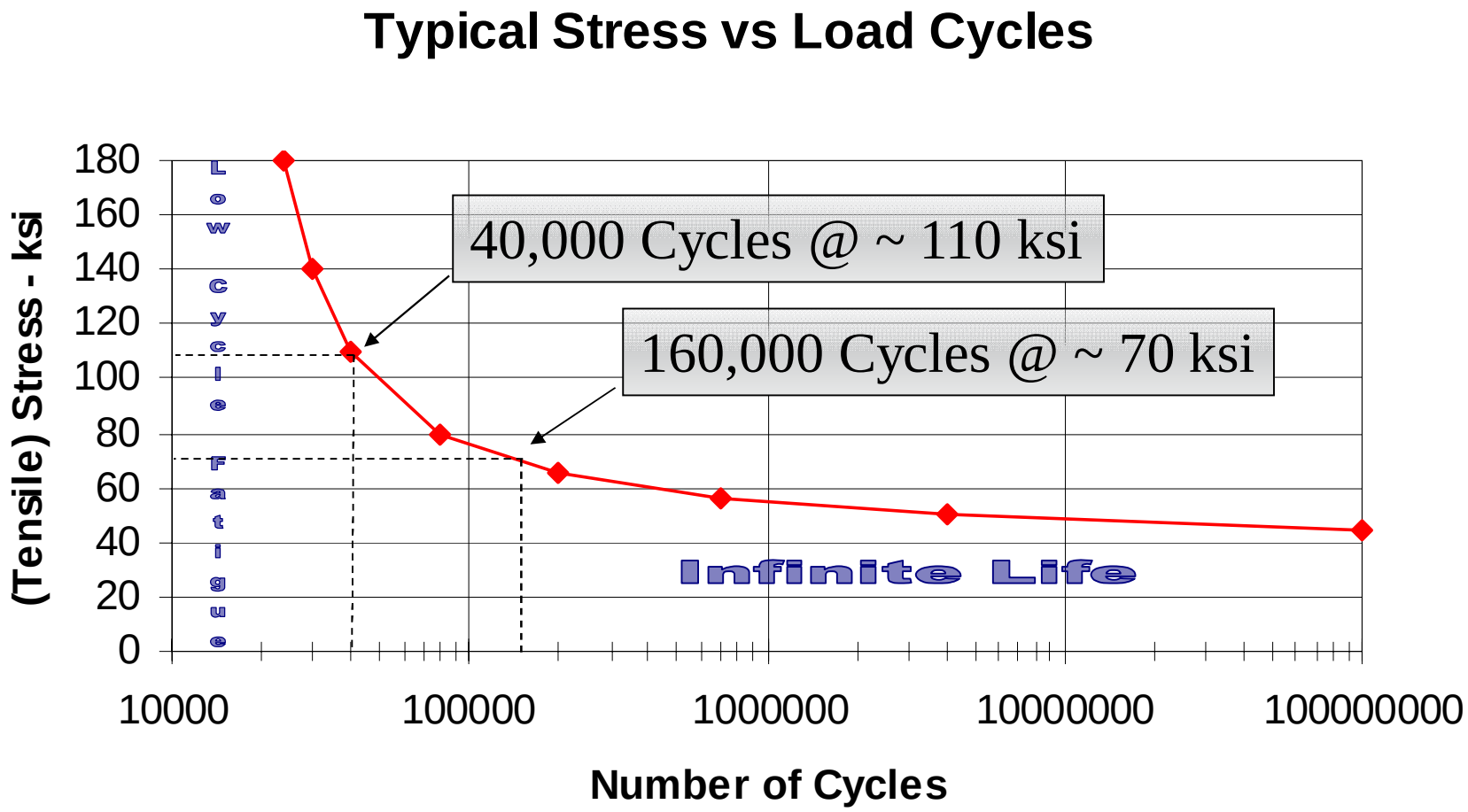
Shot Peening: Linear Decrease in Tensile Stress = Exponential Increase in Fatigue Life



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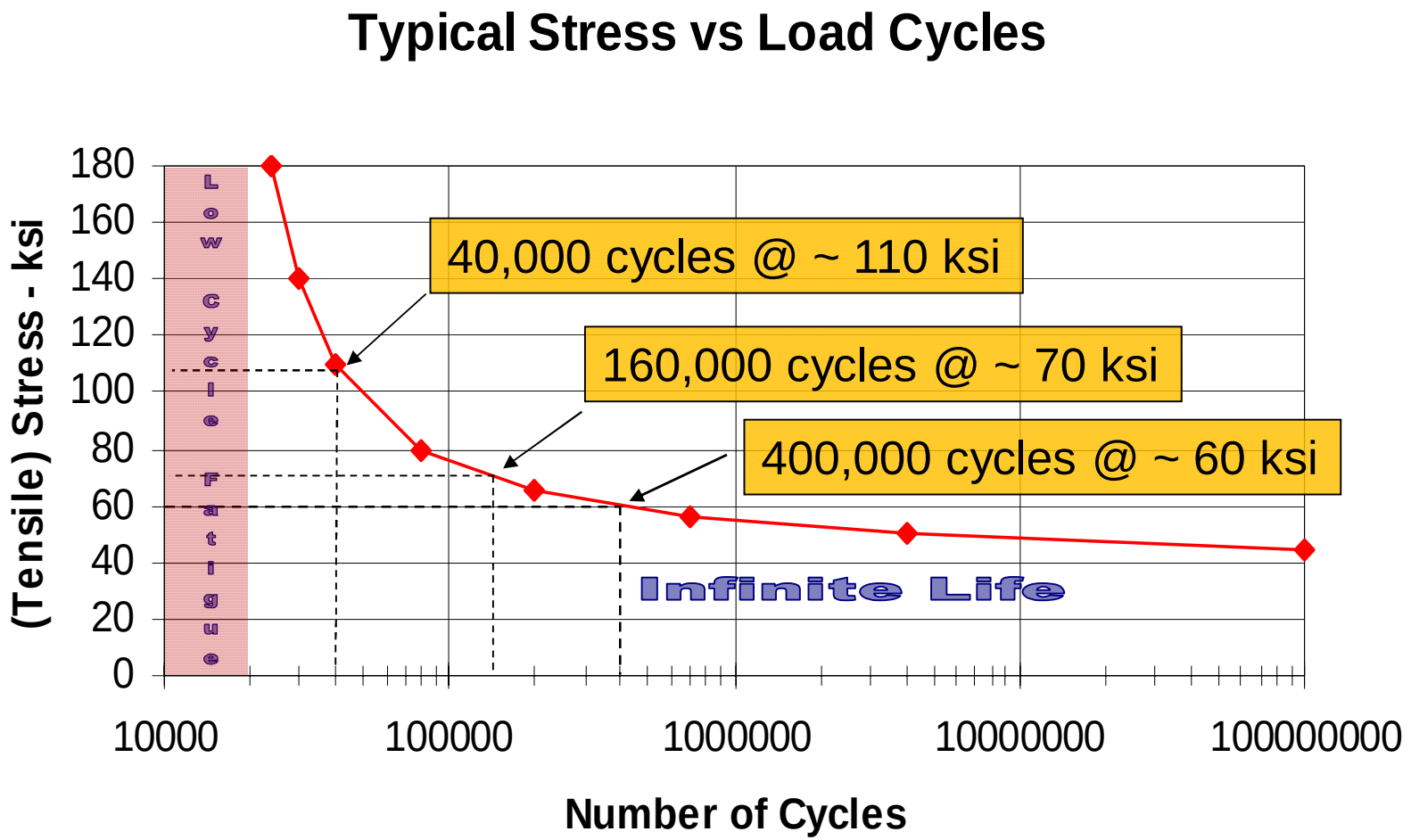
Linear Decrease in Tensile Stress = Exponential Increase in Fatigue Life



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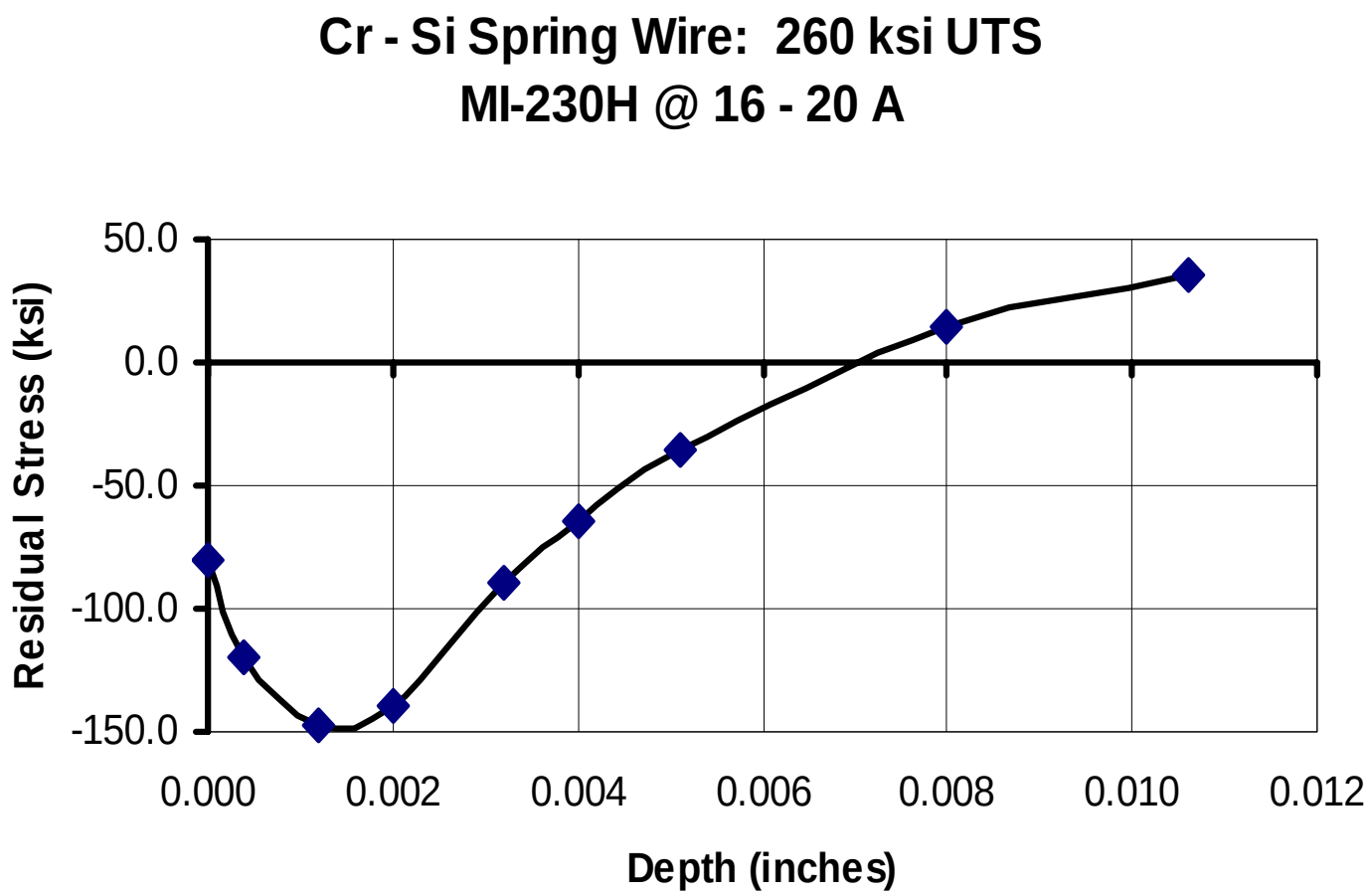
Typical Shot Peening Residual Stress Profile



Surface Stress

~ 85 ksi

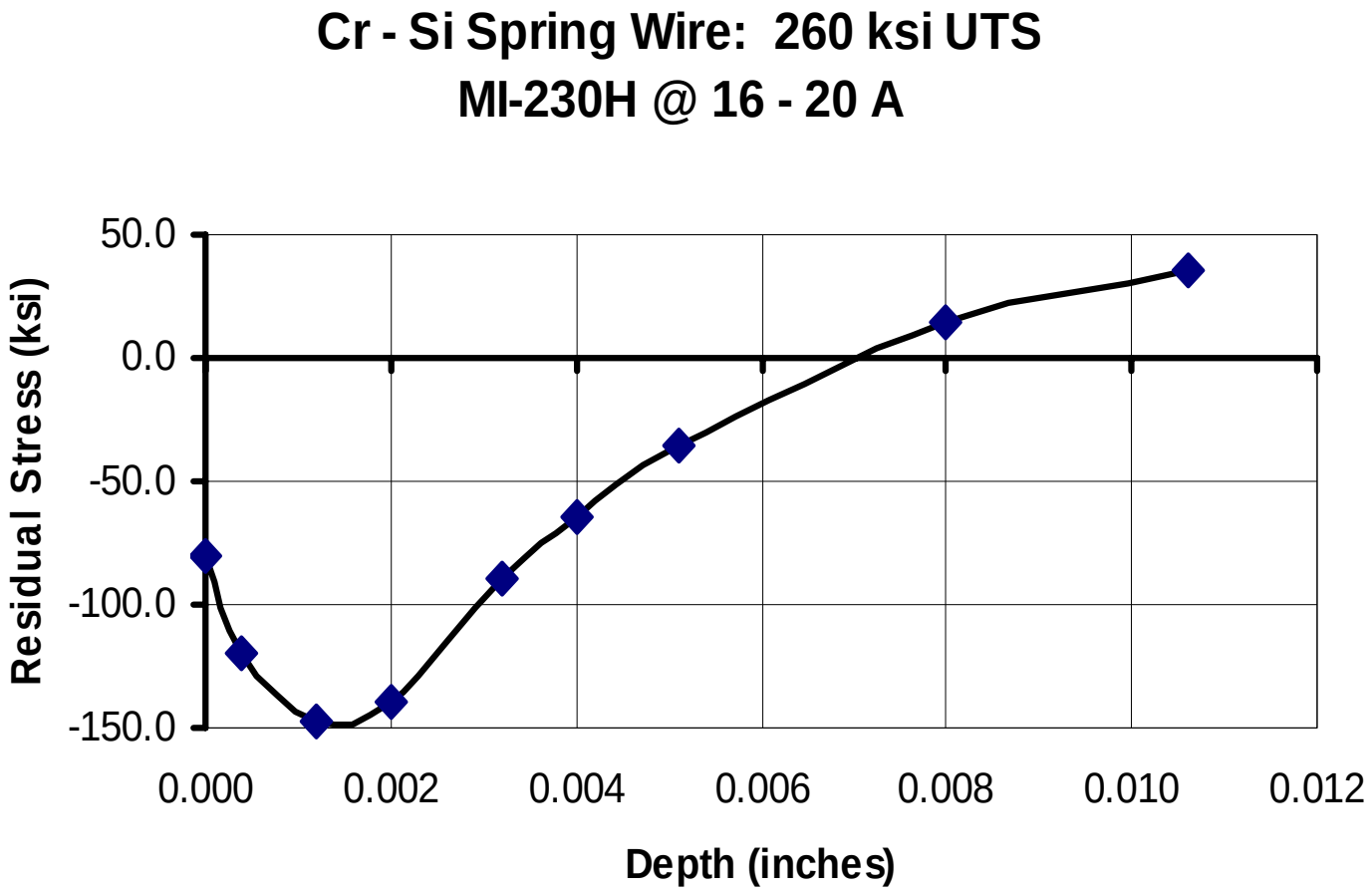
Max. Compr. Str

~ 150 ksi

Depth of Compr.

~ .007”

Typical Shot Peening Residual Stress Profile



Surface Stress

~ 85 ksi

Max. Compr. Str

~ 150 ksi

Depth of Compr.

~ .007”

The Surface is Important

- Applied stress from loading is the highest (torsional stress) at the surface.
- Residual stress from coiling (tensile) is the highest at the surface.
- Residual stress from shot peening (compressive) is the highest at the surface.
- Fatigue cracks start at the material's surface.

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Shot Peening Iterations

- No shot peening vs shot peening
- Regular hardness shot vs hard shot
- Lower intensity vs higher intensity
- Single peening vs dual peening
- Post shot peening bake vs no post peen bake
- Order of shot peening & cold pressing

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Cold Pressing Was Required

- Due to very high test stress (172 ksi; 61.5% of UTS), cold pressing was required.
- Without a cold press, springs would have yielded on first test cycle.
- This changes the free length and properties of the spring.
- All springs were cold pressed so proper comparisons could be made.
- Free Length:
  - ~ 17” before cold press
  - ~ 15.4” after cold press

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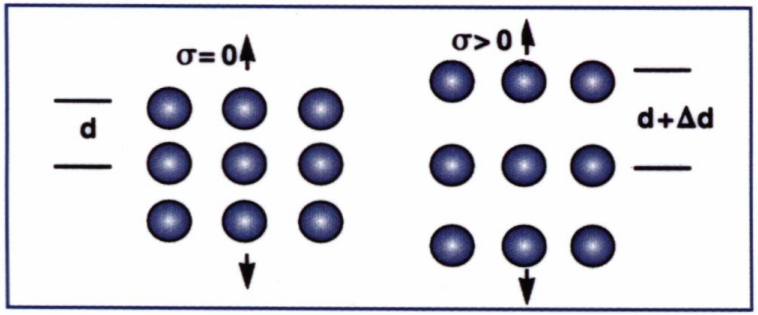
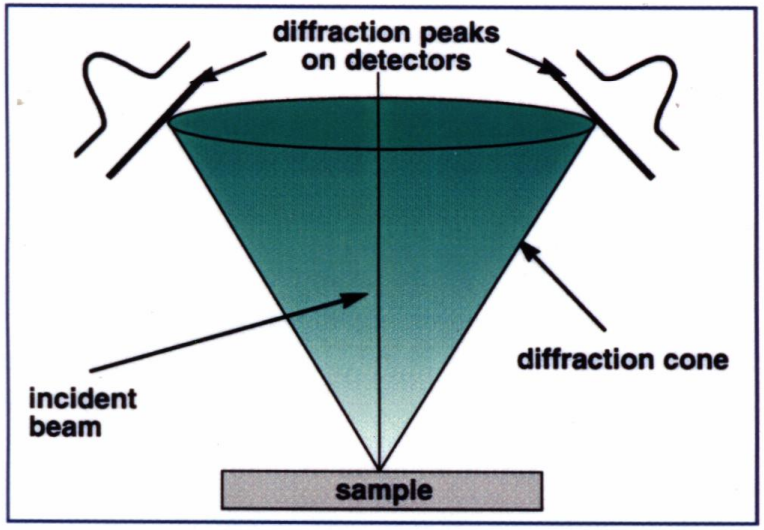
X-Ray Diffraction (XRD)
Measurement of Residual Stress

- An x-ray beam will reflect off of a crystalline material.
- Angle of this reflected beam is directly related to the spacing of atoms in the material as per Bragg's Law: $I = 2d \sin q$



Changes in stress cause changes in atomic lattice spacing "d".



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X-Ray Diffraction (XRD)
Measurement of Residual Stress

- Measurement of atomic spacing will give the strain of the material.

- Strain is converted to stress via Hook's Law

$$e_{fy} = \frac{1}{2} S_2 s_f \sin^2 y - S_1 (s_{11} + s_{22}) + \frac{1}{2} S_2 t_f \sin 2y$$

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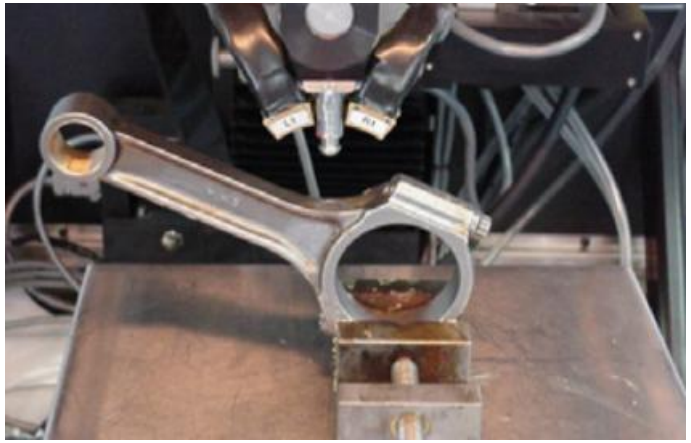
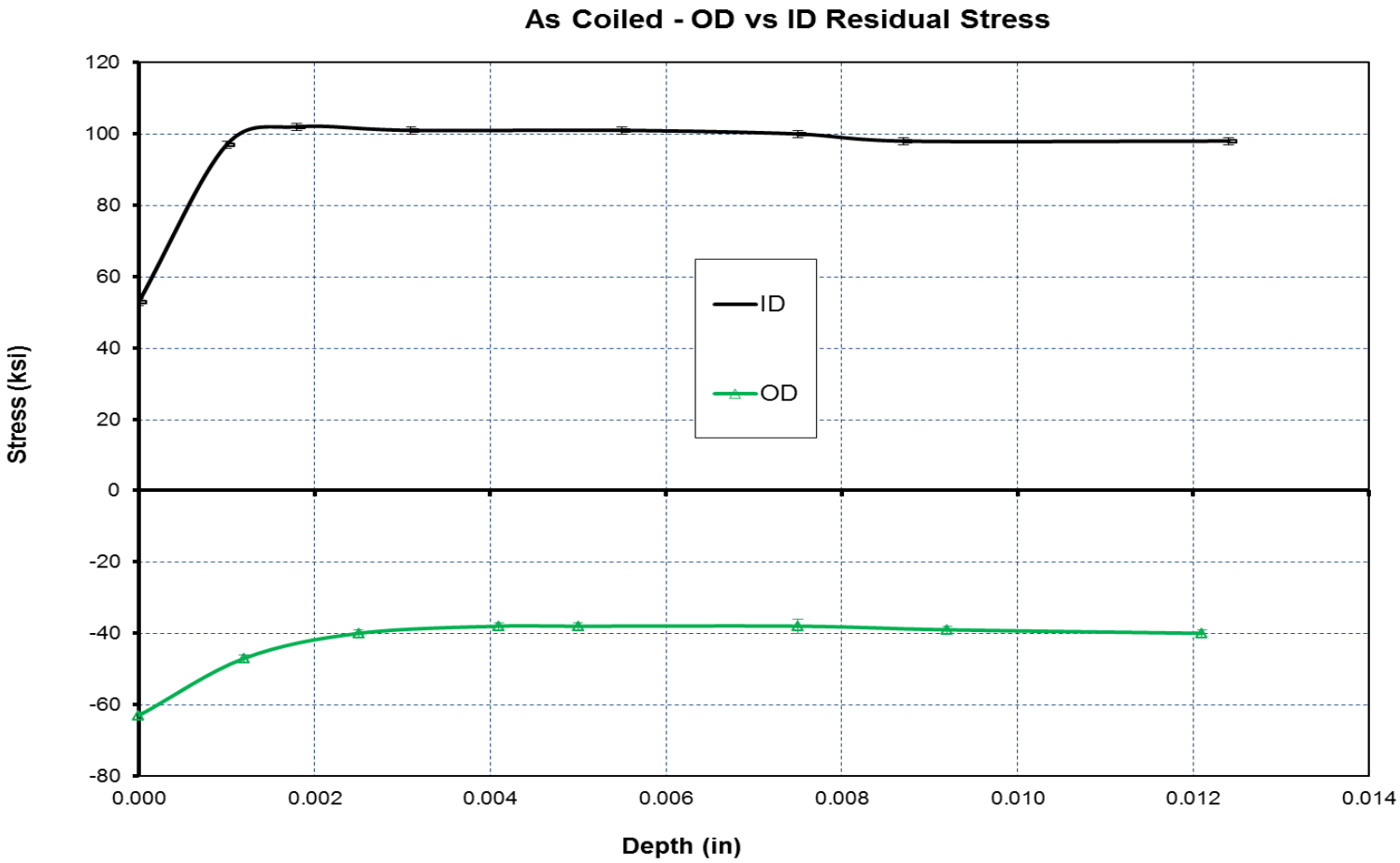
X-Ray Diffraction (XRD) Equipment (Fixed & Portable)



Baseline Spring
No Peening



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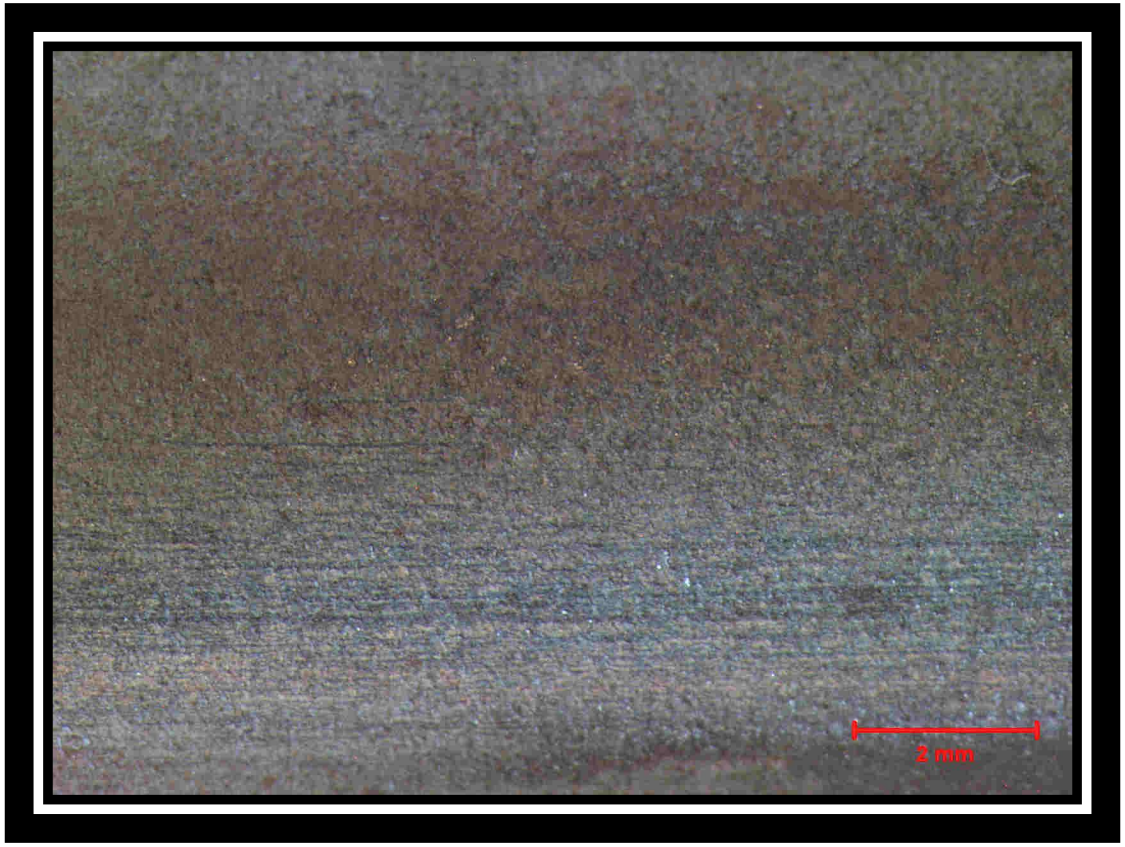
Baseline Spring - Observations



20x magnification of inner diameter

Inner Diameter

~ 60-100 ksi

Residual Tension

* Area of potential failure

Outer Diameter

~ 40-60 ksi

Residual Compression

Residual Stress Differential

ID vs OD

~ 110-140 ksi

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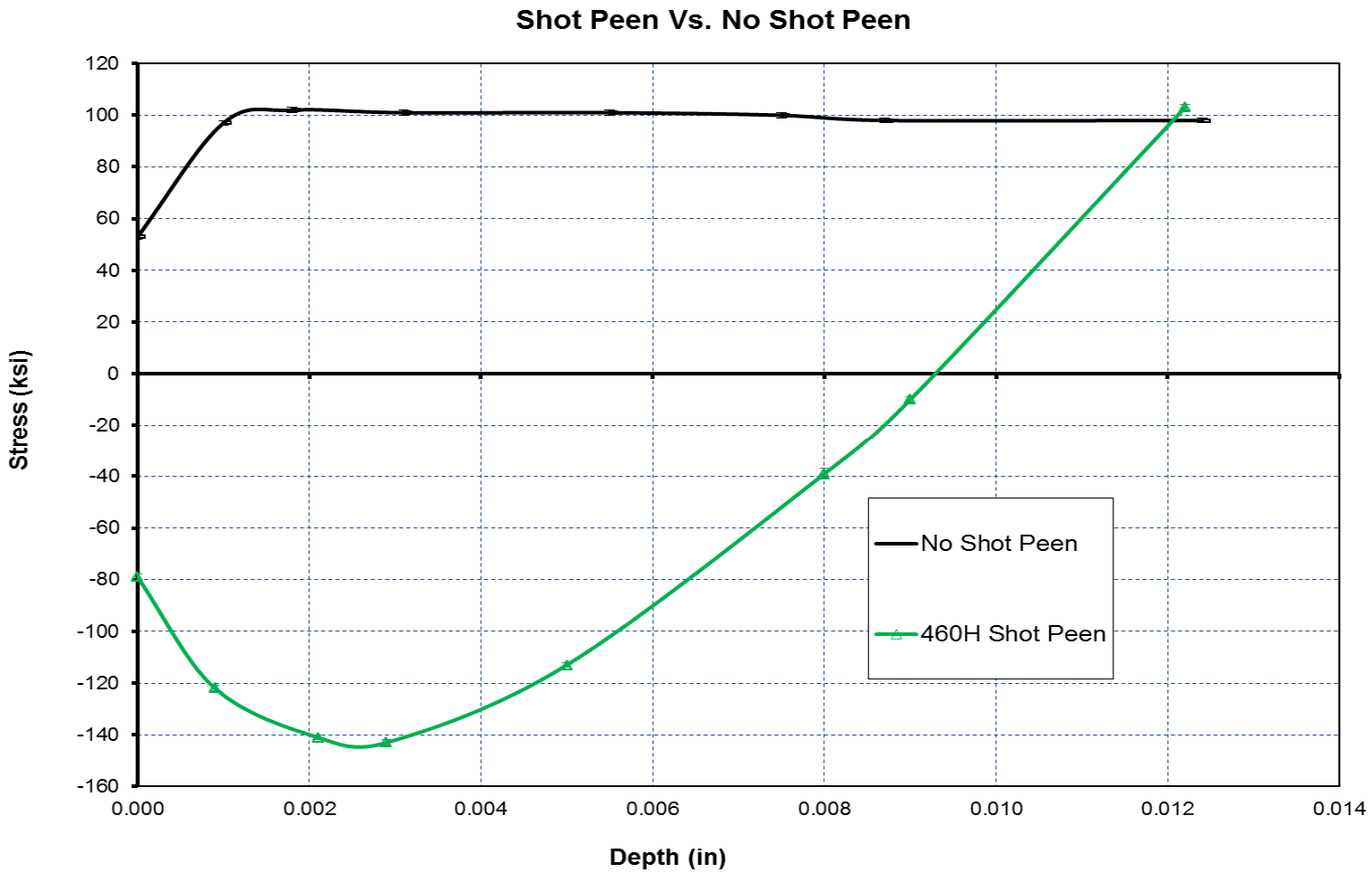
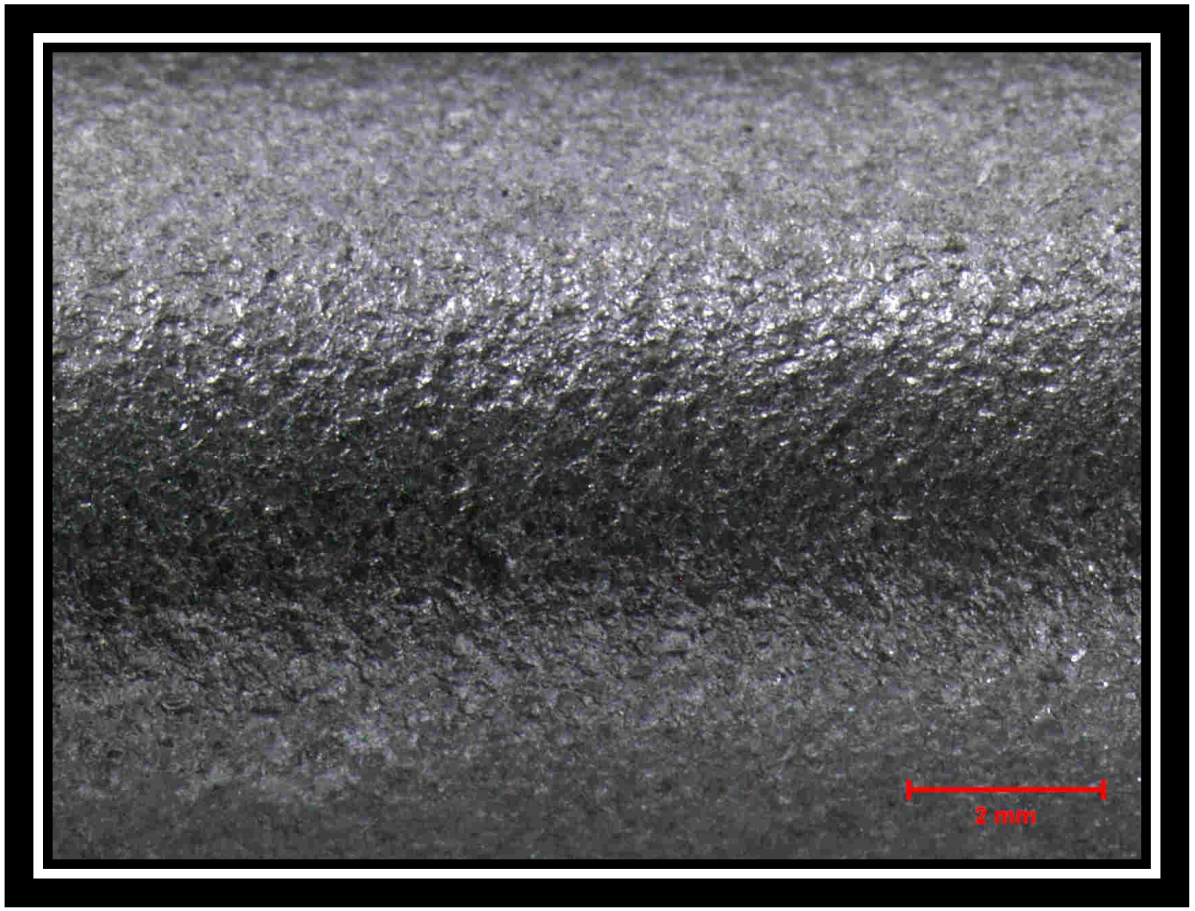
460H Shot Peened



Residual Stress at the ID of spring

460H Peened - Observations



20x magnification of
inner diameter

No Shot Peening

11,200 cycles

460H Shot Peening

74,900 cycles

Difference in Resid Stress
Before & After S/P

~ 130-240 ksi

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460H Peened – Failure Observations

20x magnification of inner diameter

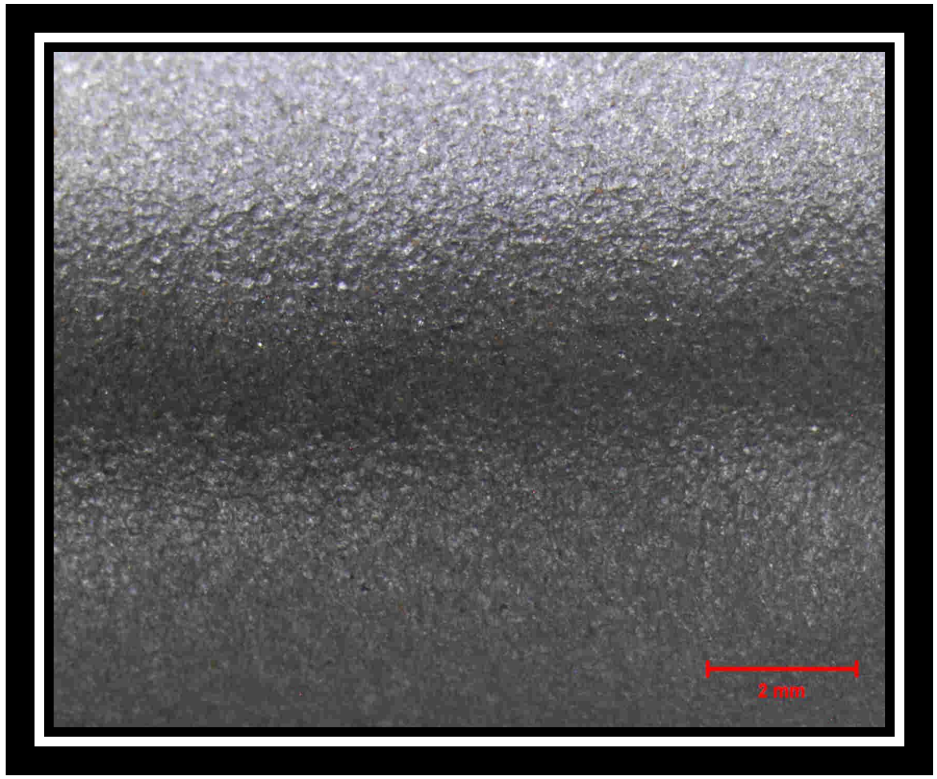
82,000 life cycles

Starts sub-surface

Observable seam.
- Fatigue cracks start at weakest location

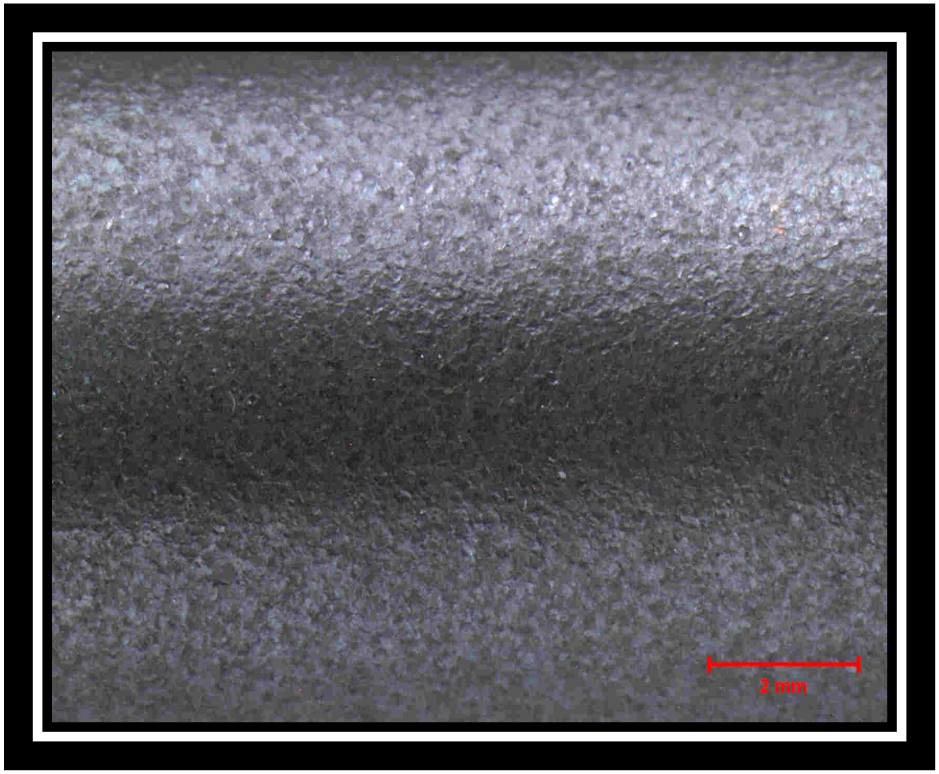
Manufacturing starts with
- square bar stock which is drawn & cold worked to round

230H & 230R Single Peen



230H

20x magnification of inner diameter



230R

20x magnification of inner diameter

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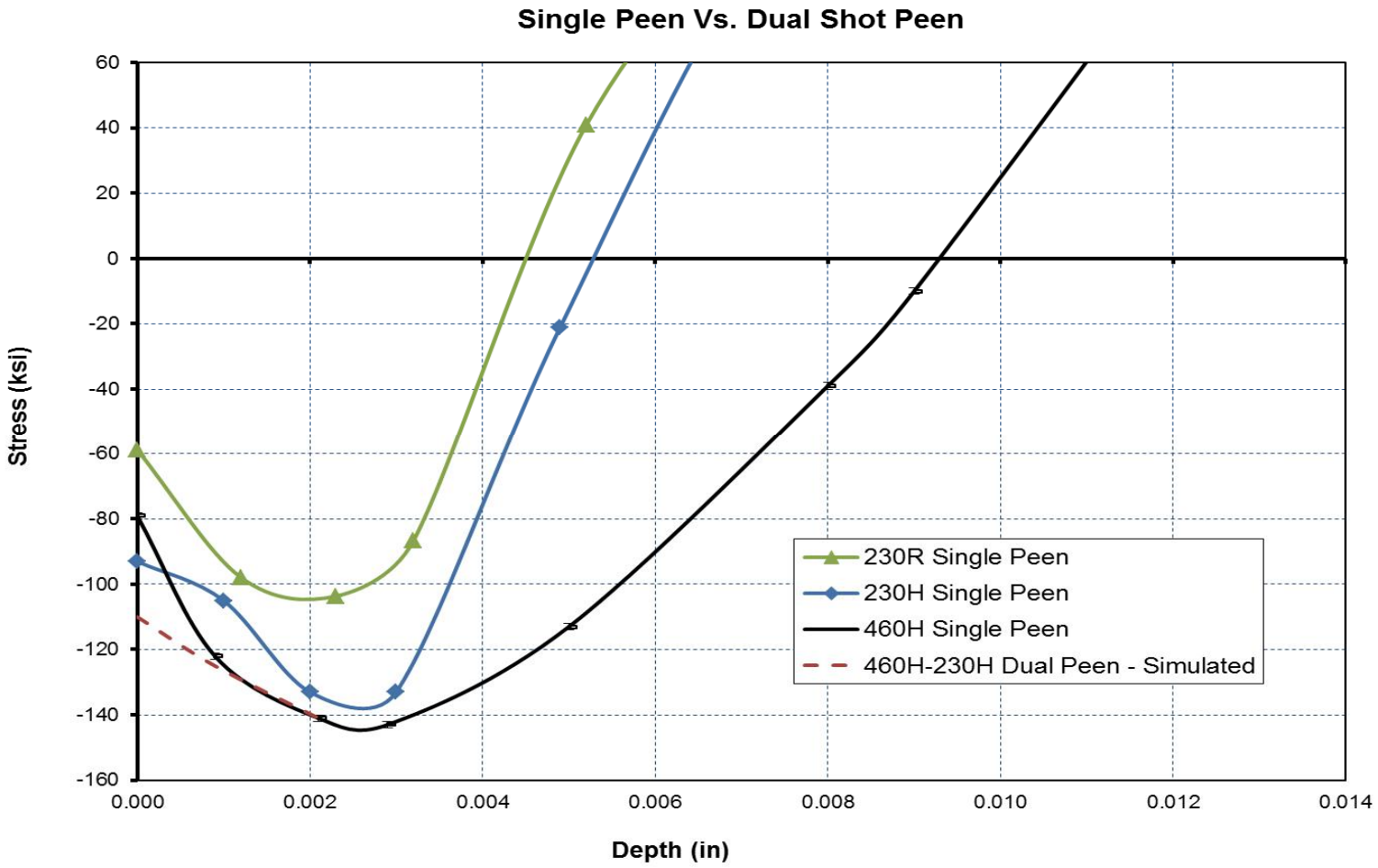
Single & Dual Shot Peened



Residual Stress at the ID of spring

Single & Dual Peened Observations

230R @ 0.012-0.016” A	53,200 cycles
230H @ 0.012-0.016” A	62,500
460H @ 0.008-0.010” C	74,900
460H-230H Dual Peen	107,000

* More residual compressive stress = More fatigue life (area under the curve)
* More intensity = More compressive depth
* 230H & 460H have about same max compressive stress
* Surface compressive stress & max compressive stress are more important that compressive depth

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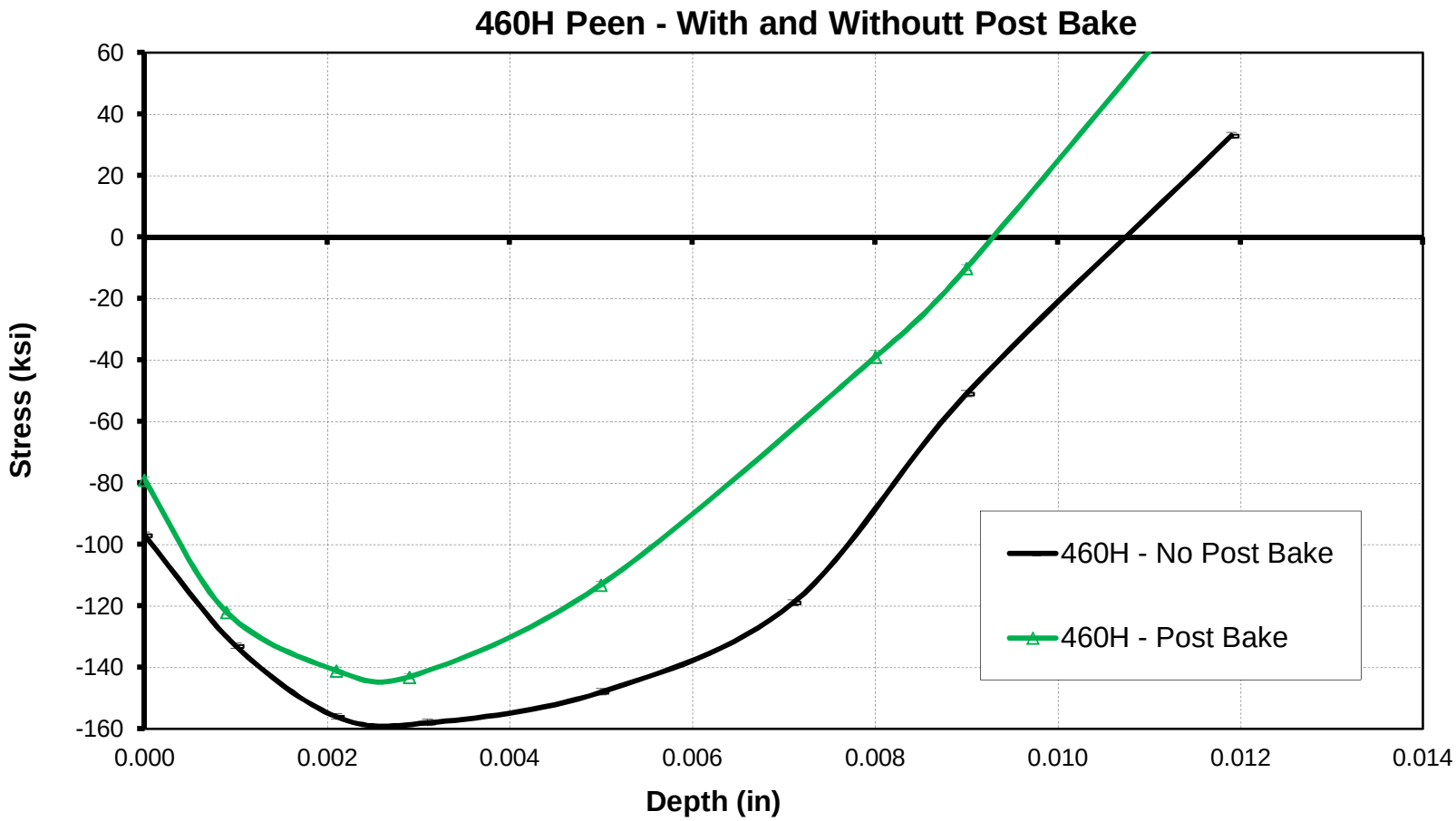
460H shot peen with & w/out Post Bake



Residual Stress at the ID of spring

460H With & W/Out Post Bake Observations

No Shot Peening	11,200 cycles
460H @ 0.008-0.010” C (with post bake)	81,900
460H @ 0.008-0.010” C (no post bake)	185,900

- Unexpected Result: Post baking of shot peened springs is well documented and accepted. The springs without post baking performed (by far) the best in this study.

* What we learned: Post shot peen baking of springs in very highly loaded applications is likely not recommended.

* See next slide: This is a more typical low stress – high cycle fatigue application with benefits of post peen bake

Fatigue Study on Shot Peen Post Bake Temp

No Shot Peen: 335k cycles (100% failure rate)

Shot Peen w/No Bake: 4.4 M (20% failure rate)

S/p w/400 F Bake: 6.0 M (0% failure rate)

S/p w/500 F Bake: 5.4 M (40% failure rate)

S/p w/600 F Bake: 2.25 M (60% failure rate)

S/p w/700 F Bake: 0.88 M (100% failure rate)

(Note: 0 F thru 500 F tests stopped @ 6 M cycles)

(Note: 600 F thru 700 F tests stopped @ 3 M cycles)

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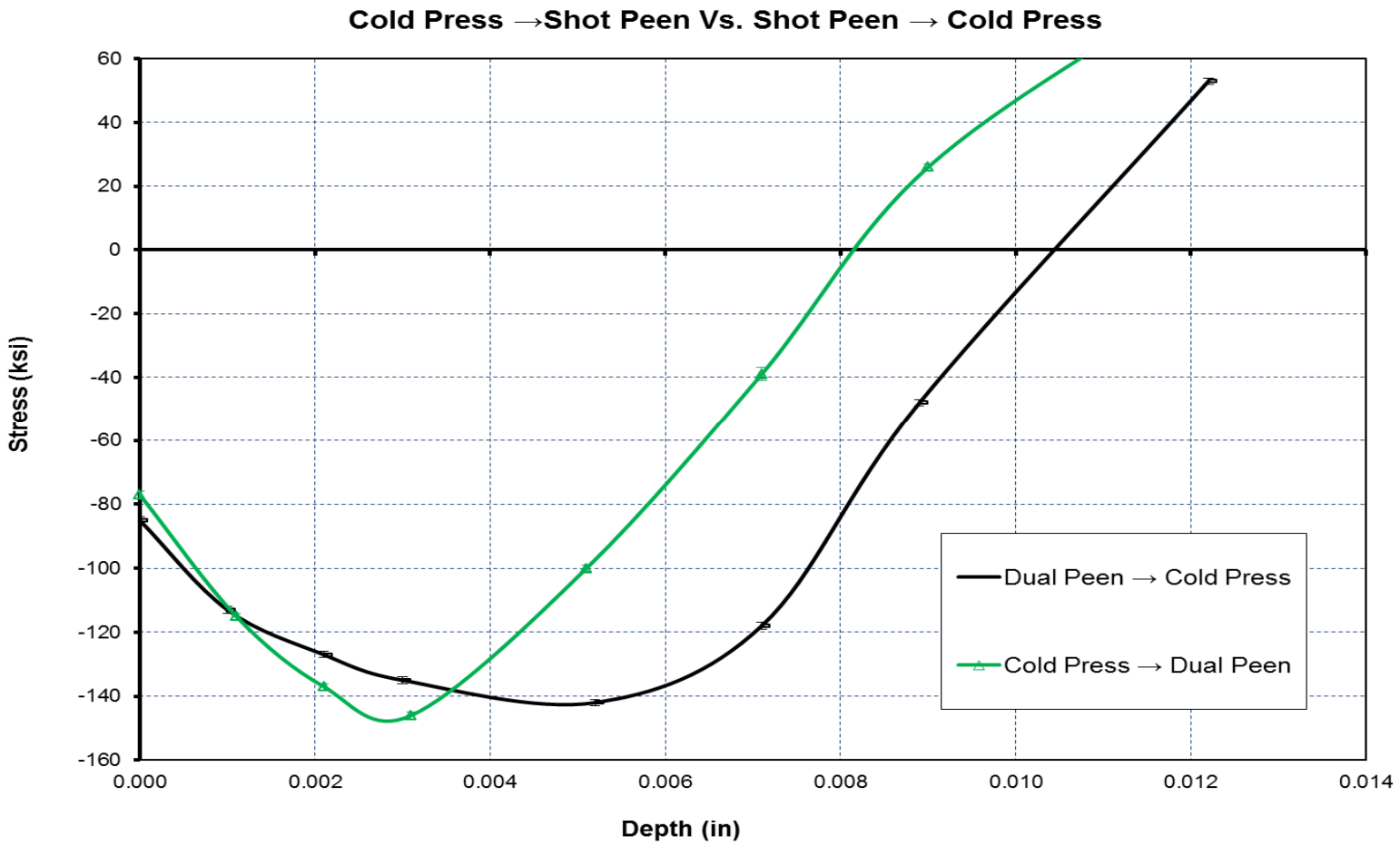
Dual Peen & Cold Press: Reverse Order



Residual Stress at the ID of spring

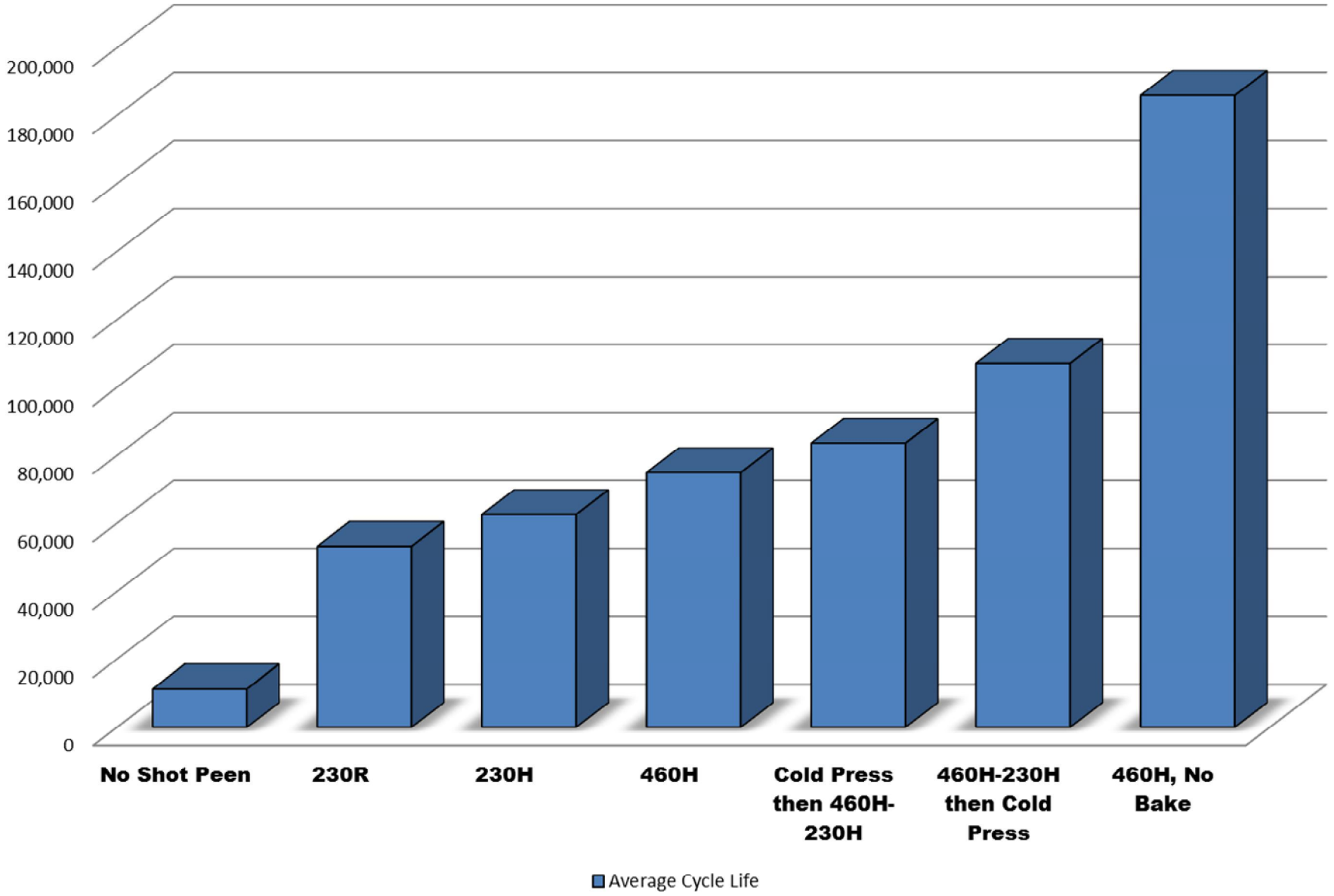
Cold Press - Dual Peened Reversal Observations

460H-230H Dual Peen then Cold Press	107,000
460H-230H Cold Press then Dual Peen	83,600

* Most commonly shot peening happens before cold press. This is better for holding spring tolerance.

* The cold press is able to drive the compressive stress curve deeper.

Fatigue Life Summary: All Iterations



Continuation of Fatigue Study

- New Spring Designed (smaller Ø wire):
  - Same test stress
  - Reduced load on fatigue test stand
- Evaluation of additional peening operations
- Evaluation of post peen temperature on fatigue life
- Evaluation of alternative media combinations
- Evaluation of spring ‘set’ throughout fatigue life

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Acknowledgements

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Proto Manufacturing (Taylor, MI)

X-Ray Diffraction Residual Stress Measurements

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Shot Peening

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Surface Photography Images

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